

Damage Tolerance Assessment of Friction Pull Plug Welds

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Abstract

Friction stir welding is a solid state welding process developed and patented by The Welding Institute in Cambridge, England (1, 2). Friction stir welding has been implemented in the aerospace industry in the fabrication of longitudinal welds in pressurized cryogenic propellant tanks. As the industry looks to implement friction stir welding in circumferential welds in pressurized cryogenic propellant tanks, techniques to close out the termination hole associated with retracting the pin tool are being evaluated. Friction pull plug welding is under development as a one means of closing out the termination hole. A friction pull plug weld placed in a friction stir weld results in a non-homogenous weld joint where the initial weld, plug weld, their respective heat affected zones and the base metal all interact. The welded joint is a composite, plastically deformed material system with a complex residual stress field. In order to address damage tolerance concerns associated with friction plug welds in safety critical structures, such as propellant tanks, nondestructive inspection and proof testing may be required to screen hardware for mission critical defects. The efficacy of the nondestructive evaluation or the proof test is based on an assessment of the critical flaw size in the test or service environments. Test data relating residual strength capability to flaw size in two aluminum alloy friction plug weld configurations is presented.

Background

A friction pull plug weld placed in a friction stir weld results in a non-homogenous weld joint where the initial weld, plug weld, their respective thermo-mechanical and heat affected zones and the base metal all interact. The welded joint is a composite, plastically deformed material system with a complex residual stress field. The non-homogeneity of the joint resulting from the material discontinuities complicates the damage tolerance assessment of the joint. Basic macroscopic features in a friction pull plug weld system are shown in Figure 1.

Basic elements that affect the damage tolerance behavior of a friction pull plug welded joint include base metal alloy combinations, plug weld size, material thickness, residual stress state, base metal strength, process parameters for the initial friction stir weld and the friction pull plug weld (including cleaning) and the nature of defects generated by the weld processes. Basic elements in a damage tolerance assessment of any welded joint include weld process control, static strength and mission life capability of a weld with defects, non-destructive evaluation, and proof test.

Damage tolerance capability of the friction plug weld material system must be grounded in test data. The residual stress state, variations in material properties, variation in sizes and location of the thermo-mechanical affected zones and their interaction with flaws or defects makes analytical predictions of stress intensity solutions somewhat problematic. For the same reasons, analytical service life predictions are also difficult, with the added complication of requiring accurate crack growth rate data. As a result, fracture testing of plug weld samples is necessary to understand damage tolerance capability. Damage tolerance capability in the form of residual strength behavior as determined by surface crack tension testing of two aluminum

alloy friction plug weld systems is presented. Tests were conducted on an aluminum-copper bi-metal alloy system and an aluminum-lithium alloy system.

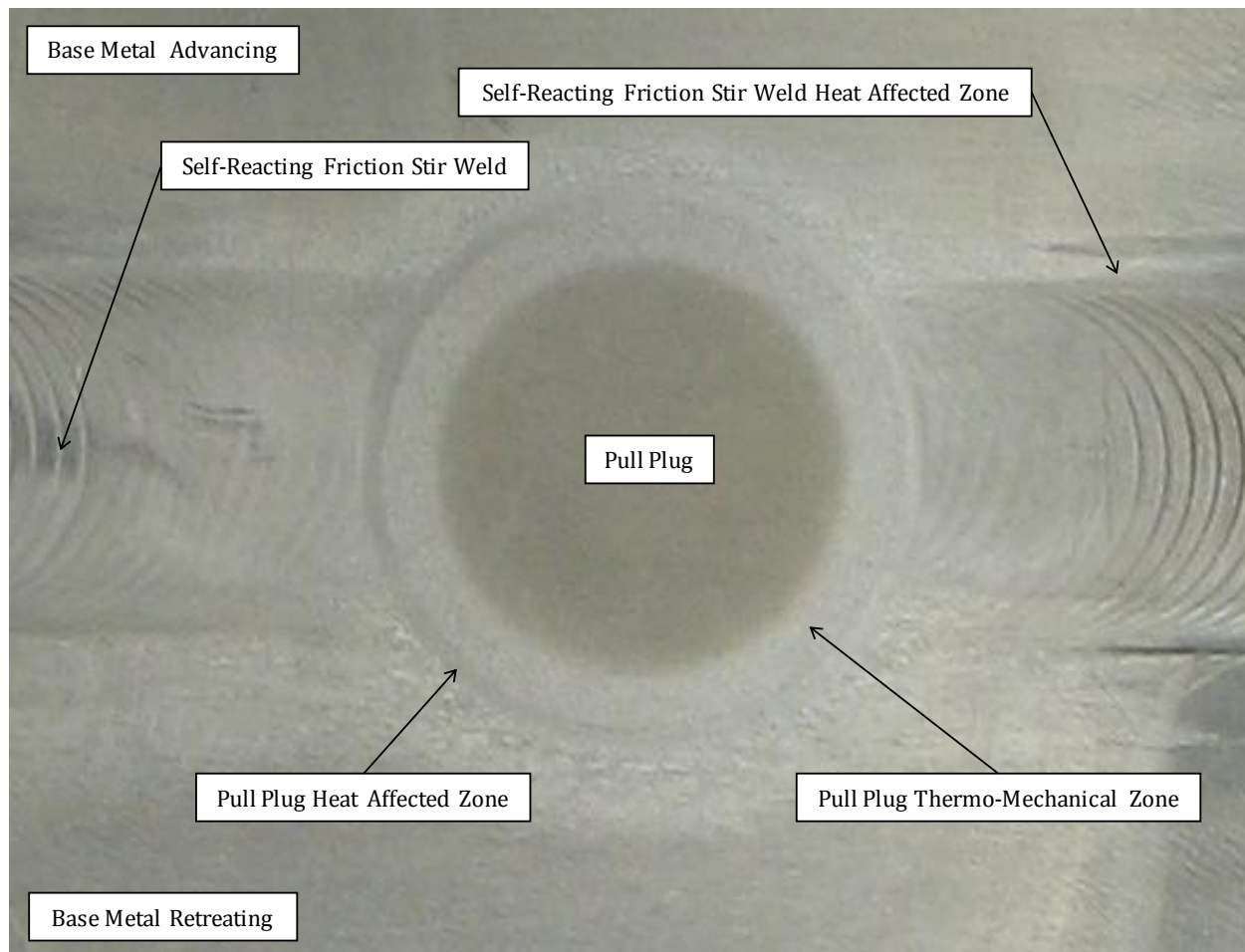


Fig. 1: Image of plug weld illustrating multiple materials and process zones.

Critical flaw size estimates can be determined from residual strength testing of surface crack tension (SCT) samples with fatigue pre-cracks grown from electro-discharge machined (EDM) notches. A photograph of an SCT sample is shown in Figure 2. In this figure, a clip gage has been inserted in the mouth of the surface crack to monitor crack mouth displacement as a function of load. A photo of a plug weld fracture surface with EDM notch and precrack is shown in Figure 3. All test samples were EDM notched and then fatigue pre-cracked in tension. Final surface crack flaws had aspect ratios (surface crack depth/surface crack length) of approximately 0.5. Tests were conducted in laboratory air and in liquid nitrogen. In reporting test results, residual strengths were normalized with respect to the average room temperature strength of a plug weld with no defects. Flaw sizes were normalized in terms of the flaw depth (a) to base metal thickness (t).

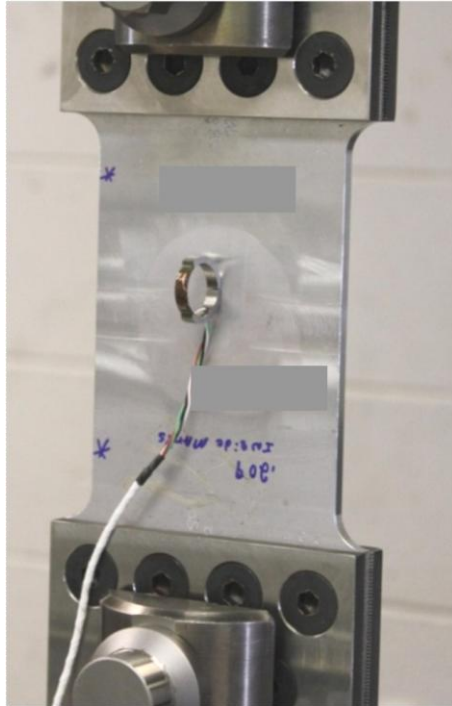
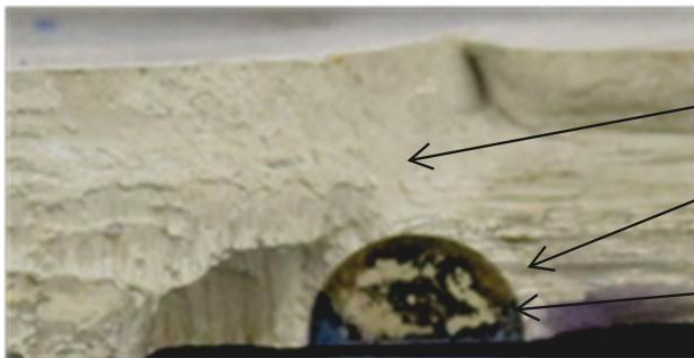


Fig. 2: Photograph of surface crack tension test sample.



Fracture Surface

Fatigue Precrack

EDM Notch

Fig. 3: Photograph of surface crack failure surface with electro-discharge machined notch and fatigue precrack.

Aluminum-Copper Alloy System

Tests on the aluminum-copper alloy system were conducted on a bi-metal material combination. Although both materials were aluminum-copper alloys, the advancing side base metal was different from the retreating side base metal. In these tests, notches and subsequent fatigue cracks were located at the top of the plug/base metal interface as shown in Figure 4. Test results are shown in Figure 5. All tests were conducted on 4 inch wide panels. As noted in Figure 5, four data points did not fail through the fabricated flaw. However, the flaws did influence the residual strength and were considered relevant to the damage tolerant capability of the material system. Depths of these flaws could not be measured and were estimated assuming a flaw depth to length aspect ratio of 0.5. Although the data set is limited, a couple of distinct trends are evident. The room temperature and cryogenic temperature residual strength

exhibits an inverse square root signature consistent with linear-elastic fracture mechanics. There is a cryogenic strength enhancement at -320°F of approximately 1.25 for plug welds with no defect. The cryogenic residual strength enhancement remains constant at an approximate value of 1.15 across a range of flaw sizes. A constant cryogenic residual strength enhancement factor improves the effectiveness of room temperature proof tests at screening flight critical defects at cryogenic service temperatures. This is particularly beneficial in a complex weld joint configuration.

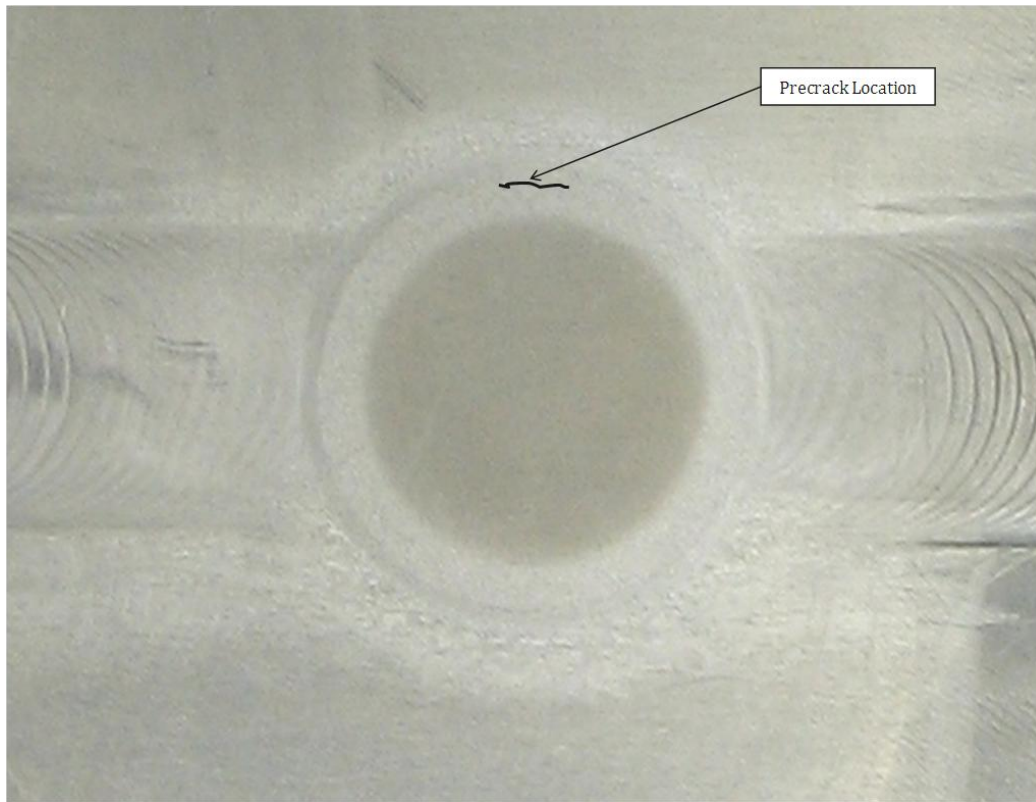


Fig. 4: Image of plug weld illustrating approximate precrack location for aluminum-copper alloy tests.

Aluminum-Lithium Alloy System

Tests of an aluminum-lithium alloy were conducted on panels with the same base metal, i.e., the advancing side base metal is the same as the retreating side base metal. In this series of tests, all of the notches and subsequent fatigue cracks were located at the intersection of the friction plug weld and the advancing side of the initial self-reacting friction stir weld as shown in Figure 6. Test results are shown in Figure 7. All tests were conducted on 4 inch wide panels. As with the aluminum-copper alloy testing, the data set is limited, but a couple of distinct trends are evident. There is a cryogenic strength enhancement at -320°F of approximately 1.15 for plug welds with no defect. At both room and cryogenic temperatures, the residual strength decreases as the flaw size increases. However, the shape of the response is not characteristic of linear-elastic fracture mechanics and may reflect net section stress effects. In contrast to the aluminum-copper alloy system, the cryogenic residual strength enhancement decreases gradually until it reaches a value of unity at an a/t ratio of approximately 0.75. This “cross-over” behavior can be problematic with respect to the effectiveness of room temperature proof tests to screen flight critical defects at cryogenic service conditions.

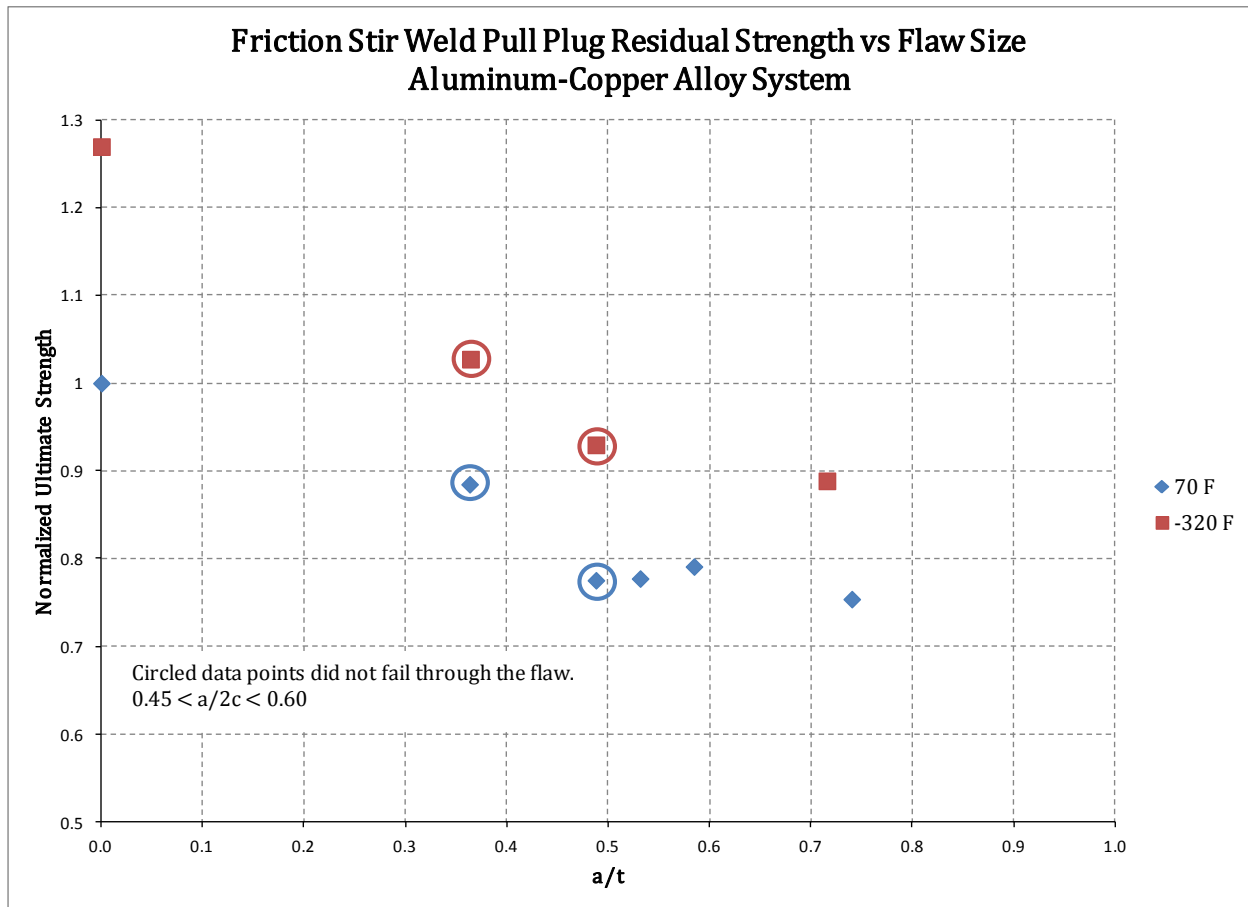


Fig. 5: Plot of residual strength versus flaw size for aluminum-copper alloy tests.

Summary

The aluminum-copper alloy plug system exhibits a cryogenic residual strength enhancement that is approximately constant with respect to flaw size. The aluminum-lithium alloy plug system exhibits a cryogenic residual strength enhancement that decreases with flaw size and reaches a cross-over point at an a/t ratio of approximately 0.75.

For both alloy systems, for the thickness tested, designs at ambient conditions, with a safety factor of 1.4 on the ultimate tensile strength, exhibit a critical flaw depth of approximately 70% of the material thickness. At cryogenic conditions, the critical flaw sizes for designs with a safety factor of 1.4 are 50% of the material thickness for the aluminum-copper alloy system and 70% of the material thickness for the aluminum-lithium alloy system. In either case, with an approximate depth to length aspect ratio of 0.5, these surface flaws can be reliably detected with liquid penetrant nondestructive evaluation [3].

With respect to proof testing as a screen for mission critical defects the aluminum-copper alloy weld system supports a traditional proof test logic approach where a given proof factor screens for a range of flaw sizes. In contrast, in the aluminum-lithium alloy weld system the proof test may only be effective up to a limiting flaw size.

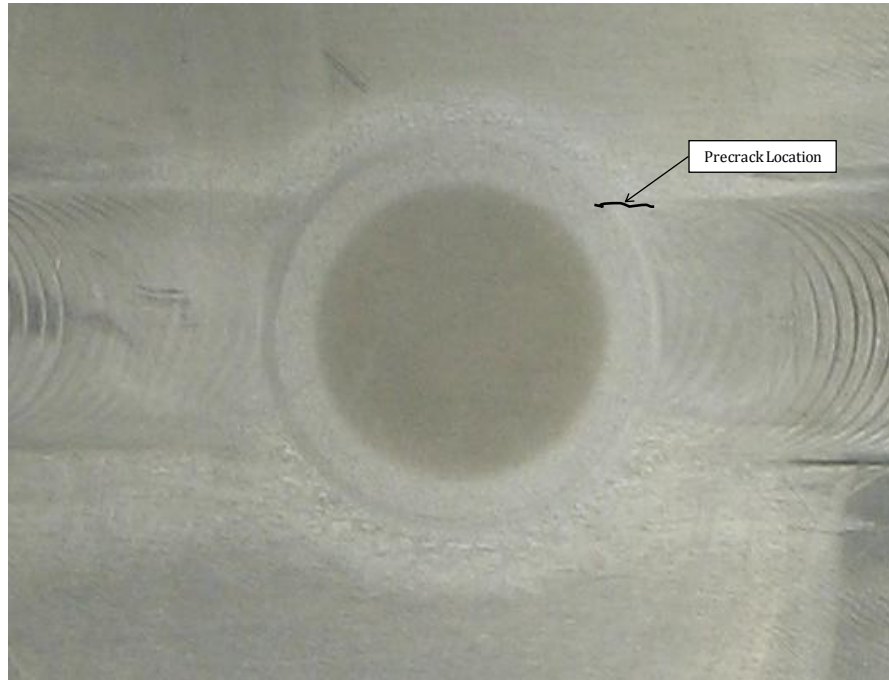


Fig. 6: Image of plug weld illustrating approximate precrack location for aluminum-lithium alloy tests.

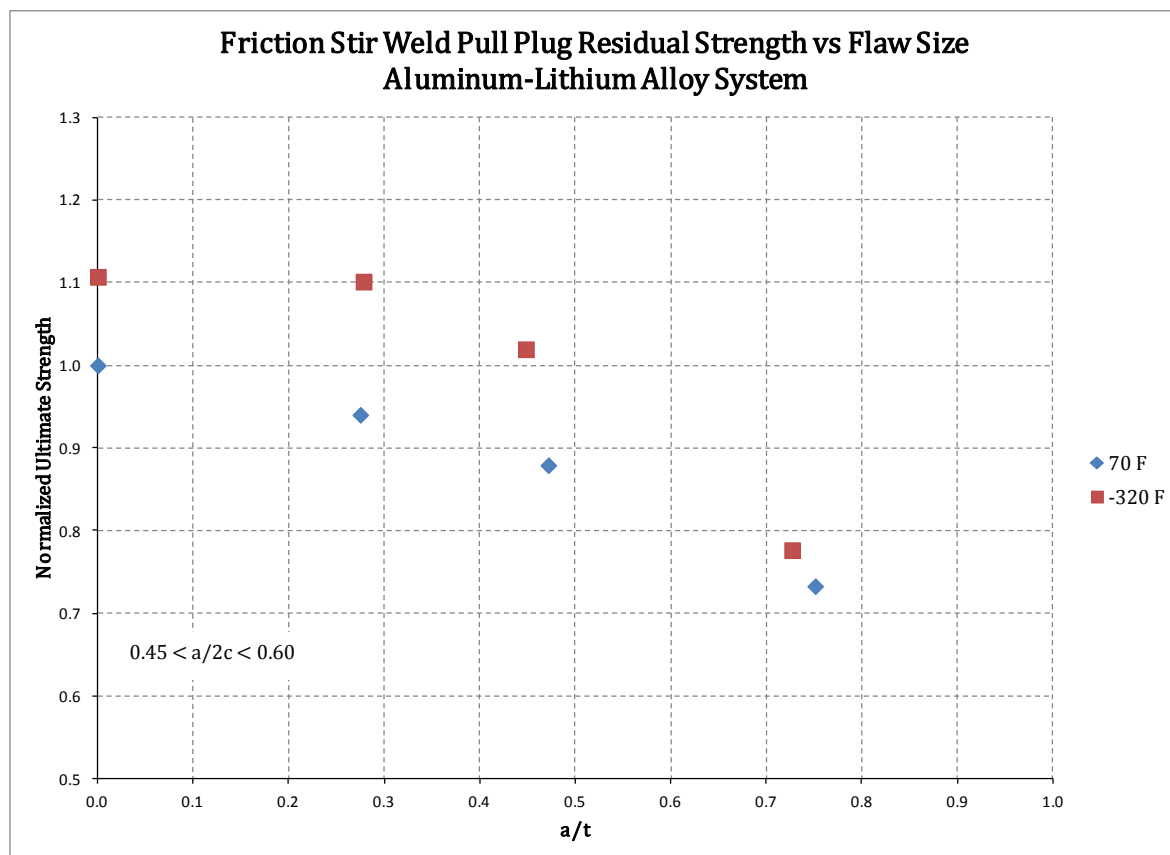


Fig. 7: Plot of residual strength versus flaw size for aluminum-lithium alloy tests.

References

1. Thomas, W.M.; et al.: "Friction Stir Butt Welding," International Patent Application No. PCT/GB92/02203 and GB Patent Application No. 9125978.8, December 1991.
2. Nunes, A.C. Jr., "Welding as Science: Applying Basic Engineering Principles to the Discipline," NASA TM-2010-216449, October, 2010.
3. NASA Technical Standard 5009, NASA-STD-5009, Nondestructive Evaluation Requirements for Fracture Critical Metallic Components, April, 2008.